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Handling Qualities Evaluation of Piloting Tools for Spacecraft Docking in Earth Orbit

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A piloted simulation was conducted to study handling qualities for the final phase of spacecraft docking in Earth orbit. Twelve evaluation pilots, including 10 pilot astronauts, provided Cooper–Harper ratings, task load index component ratings, and qualitative comments. The piloting task was manual translational control with automatic attitude hold during the final 10 ft (3 m) of the approach to docking. A previous study established that with conventional translational control, handling qualities for this task degrade significantly as the level of translation-into-rotation dynamic coupling increases. The goal of the present study was to evaluate the efficacy of various piloting tools designed to mitigate the handling qualities degradation caused by this coupling. Four piloting tools were evaluated: deadband indicator, flight-path marker, translational flight director, and feedforward control. These piloting tools improved handling qualities, generally with greater improvements resulting from using these tools in combination. A key result of this study is that feedforward control effectively counteracts coupling effects while significantly decreasing propellant consumption, providing satisfactory handling qualities for the spacecraft configuration evaluated.

Nomenclature

$\boldsymbol{A}$ = matrix of acceleration components due to control jet firings, $\mathrm{m/s^2}$ or $\mathrm{deg/s^2}$
J = scalar cost function
$\Delta \boldsymbol{t}$ = vector of control jet firing times, s
$\Delta \boldsymbol{v}$ = vector of translational and rotational velocity changes, m/s or deg/s

I. Introduction

HANDLING qualities are those characteristics of a flight vehicle that govern the ease and precision with which a pilot is able to perform a flying task [1]. They are a manifestation of the interaction between various factors that influence pilot perception of how well (or poorly) a vehicle can be flown to accomplish a desired mission. These factors include the basic stability and control characteristics of the vehicle, the control systems that modify these characteristics, the inceptors (e.g., control column or throttle lever) used by the pilot to transmit control commands, the visual cues from cockpit windows and displays/instrumentation that provide flight information to the pilot, and other cues (e.g., aural, tactile) that affect the pilot in the execution of the flying task.

The effects of the above factors on handling qualities have been studied in atmospheric flight vehicles over many decades [2–6]. Standards for the handling qualities of both fixed-wing aircraft [7] and rotary-wing aircraft [8] have been developed and are now in common use. Broadly speaking, these standards define a subset of the dynamics/control design space that provides good handling qualities for a given vehicle type and flying task. For example, the standards may specify combinations of damping and natural frequency for a large aircraft during landing that correspond to satisfactory, acceptable, and unacceptable handling qualities. Such standards can provide a target for dynamics/control engineers during the design cycle of the vehicle.

At this time, no handling qualities standards exist for spacecraft. However, there exists a body of work on handling qualities of piloted spacecraft. During NASA's Gemini and Apollo programs, studies were conducted on spacecraft handling qualities for rendezvous and docking [9–13]. These studies used the Cooper rating scale [1], which was a precursor of, and quite different from, the Cooper–Harper rating scale that has been widely used in handling qualities studies since the early 1970s. In large part, the Gemini/Apollo studies attempted to determine the preferred mode for manual control of attitude [14–19], the utility of television (TV) cameras to conduct remote and obstructed-view dockings [19,20], the optimum combination of out-the-window visual aids to allow instrument-free dockings [14,16–18,20], ideal inceptor characteristics [21], limits on target oscillatory motion [15], the effect of docking during orbital night versus day [16,18], the consequences of failed thrusters [14], and the handling qualities ratings of the specific Gemini and Apollo vehicles as a function of these parameters [14,17,19]. Those tests showed that for manual attitude control, a rate command with attitude hold (RCAH) mode was favored over a simple rate-command or acceleration-command mode [19], and all vehicles starting with Gemini have used or are currently able to use that mode of controlling attitude. TV cameras were shown to be viable sensors for conducting dockings once the pilot learned to compensate for the degraded visual scene and difficulty in estimating range and range rate [20]; remote cameras are currently being used for space shuttle docking operations. The standoff cross and collimated reticle were identified as the primary tools for estimating relative state errors during the final phase of docking, and they were used in the Apollo program for crew/service module docking with the lunar module [18]. Several fixed-base [17,19] and six-degree-of-freedom motion [14,17] simulators were used to evaluate these combinations, and results indicated that with the RCAH mode and a good set of visual cues the handling qualities of the vehicles were satisfactory [19]. These results were repeatedly confirmed during follow-up simulations and confidence in the design solutions was so high that subsequent vehicles, such as the space shuttle, adopted them almost without modification. This work forms an excellent baseline from which to start designing docking control/display systems that

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provide desired handling qualities. However, improvements in navigation state accuracy, control mode sophistication and instrumentation in the decades following Shuttle development offer the possibility of making the task of manual spacecraft docking even easier.

A new generation of piloted spacecraft, such as the Orion crew vehicle [22], have been proposed to replace the space shuttle and ferry astronauts to lunar orbit. The ability of pilots to successfully carry out their missions will be determined in part by the handling qualities of these new spacecraft. Some flight operations may be fully automated, while others may be executed with a human pilot engaged in various levels of supervisory control including manual-flying tasks [23]. Current NASA procedures require that human-rated spacecraft provide the capability for the crew to manually control flight path and attitude with satisfactory handling qualities [24]. Even for flight operations that are nominally executed in a highly automated control mode, the control architecture must provide the capability for a human pilot to switch to a manual control mode: whether due to failure of an automated system, or of some component of the spacecraft. In these cases of emergency reversion to manual control, where the pilot role abruptly switches from monitoring to active control, it is important that the vehicle have acceptable handling qualities. It is therefore desirable for spacecraft designers to assess early in the design cycle what the handling qualities will likely be and to adjust their design if necessary to ensure that appropriate levels of handling qualities are available for both nominal and offnominal operations.

An effort to develop design guidelines for spacecraft handling qualities was initiated by NASA in 2007. A comprehensive set of guidelines should cover all classes of spacecraft and phases of flight; however, near-term NASA program goals made it necessary to focus initially on a few specific and relevant aspects. Lessons learned from aircraft and spacecraft handling qualities assessments over the past several decades have been compiled [25]. Preliminary studies of lunar landing [26,27] and Earth orbit docking have been conducted [28,29]. This paper reports a follow-on experiment investigating the effect of piloting tools on handling qualities for spacecraft docking in low Earth orbit; specifically, the attenuation of handling qualities degradation arising from translation-into-rotation dynamic coupling.

II. Dynamics and Control Aspects of Docking Operations

In docking operations, there is an active vehicle whose trajectory is dynamically controlled to dock with a passive target vehicle. In this paper, the following terminology is used: active docking vehicle (ADV) and target docking vehicle (TDV). In the simulation used for this work, the TDV was represented by a model of the International Space Station and the ADV was represented by a generic spacecraft whose geometry and maneuvering acceleration properties were derived from an early model of the Orion crew vehicle. The control systems and cockpit displays of the ADV were research prototypes that were developed independently from NASA's Orion Project; details are presented later in the paper.

Before docking, a rendezvous maneuver positions the ADV ahead of the TDV with a small closing rate along the orbital velocity vector of the TDV; this is known as the V-bar approach. When the distance between the two docks is about 30 ft (9.1 m), an attitude alignment maneuver is performed to match the attitude of the ADV with that of the TDV. The final approach for docking is executed with the ADV's attitude-hold system engaged; the flight control system automatically fires reaction control system (RCS) jets to produce the roll/pitch/yaw moments necessary to hold attitude within specified deadbands.

An illustration of the ADV is shown in Fig. 1; note that the docking mechanism is mounted on the nose of the vehicle. A video camera is installed on the nose of the ADV, close to the vehicle centerline. This centerline camera image is displayed to the pilot with a reticle overlay that indicates the center of the ADV docking port using crosshairs. During final approach for docking, the camera shows the TDV docking port, which has various markings, including a circle with a radius of 3 in. (7.6 cm) drawn around the center of the docking device, as depicted in Fig. 2. A standoff cross is mounted at the center of the TDV docking port; its dimensions are slightly larger than the circle mentioned above, and it is offset forward by 12 in. (30.5 cm) from the surface on which the circle is drawn.

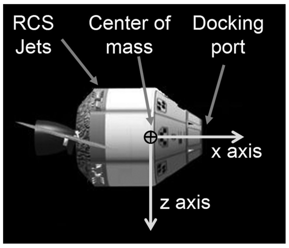

Fig. 1 Illustration of ADV.

The camera view with reticle crosshairs constitutes the minimum piloting tool set required to perform the docking task, enabling the pilot to visually estimate the position and orientation of the ADV docking port center relative to the TDV docking port center. In general, any displacement between the standoff cross center point and the reticle crosshairs intersection point reflects a composite of position and attitude errors between the ADV and TDV docking ports. For example, consider a situation where the reticle crosshairs intersection point is to the right of the TDV docking port center. This could happen if the ADV is displaced to the right of the TDV (translation error), or if the ADV is yawed to the right (attitude error), or a combination of both errors. For a successful docking, the composite radial position error must not exceed 3 in. (7.6 cm).

The pilot uses a translational hand controller (THC) to make translational control inputs as necessary to null the transverse position error between the center of the ADV docking port and the center of the TDV docking port. This generally requires pilot inputs along two translational axes: up/down inputs to make small trajectory adjustments in the orbital plane along the local vertical and left/right inputs to make small trajectory adjustments perpendicular to the orbital plane. These pilot inputs command the flight control system to fire the appropriate RCS jets to produce the appropriate translational motion. For example, the translational control system used for space shuttle docking provides a small translational velocity change of 0.01 ft/s (0.3 cm/s) along the appropriate axis for each discrete input of the THC.

An important aspect of the ADV's dynamics is the degree of coupling from translational inputs into rotational motions. This dynamic coupling arises from the longitudinal offset between the RCS jet locations and the vehicle center of mass (c.m.), and it results in a thrust coupling between translational and rotational motion that can have a significant impact on handling qualities for docking. The degree of coupling experienced by the pilot is dependent not only on the location of the RCS jets relative to the c.m. but also on the control scheme by which forces and moments are generated in response to pilot THC inputs. Coupling is defined in this work as the ratio between the disturbance angular acceleration ($\deg/s^2$) and the applied translational acceleration (m/s^2) that gives rise to the disturbance; hence, the units of coupling are $\deg/m$.

Consider a spacecraft on which the RCS jets are mounted aft of the vehicle c.m. A conventional translational control system responds to THC inputs by firing the appropriate RCS jets to create a net thrust

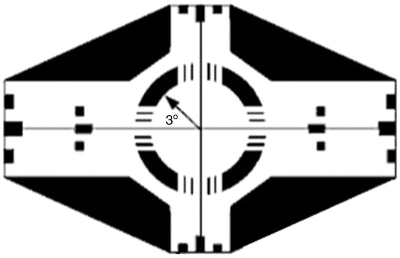

Fig. 2 Markings on TDV docking port.

force along the appropriate body axis for a precalculated time interval to provide a small increment in velocity. For example, a left THC input will produce an RCS thrust force that translates the vehicle to the left, but that force will also induce an unwanted yawing moment that rotates the vehicle's nose to the right. Since the centerline camera is mounted on the nose of the ADV and follows the net motion of the nose (caused by both translation and rotation effects), the pilot may initially perceive a motion in the "wrong" direction until the attitude-hold system engages at a deadband limit and counteracts the yawing moment. For example, an attitude-hold deadband of 0.5 deg per axis and a moment arm of 12 ft (3.7 m) from vehicle c.m. to nose would result in an equivalent translational nose motion of 1.3 in. (3.3 cm), which is almost one-half of the allowable radial position error for successful docking.

III. Piloting Tools for Docking

A prior study of piloted docking, using only the minimum piloting tool set of a centerline camera view with reticle crosshairs, found that translation-into-rotation coupling can significantly degrade handling qualities [29]. Specifically, it was determined that a coupling level of 5 deg/ft (16.4 deg/m) results in handling qualities deficiencies that warrant improvement. In the current study, piloting tools were developed with the goal of improving handling qualities in the presence of substantial translation-into-rotation coupling. These tools are described below.

A. Deadband Indicator

A previous experiment [29] revealed that a key factor in pilot compensation was predicting when the attitude-hold system would hit a deadband limit and automatically fire RCS jets to create a counteracting moment. For example, consider a scenario where the ADV has a small translation error to the left and a nose-right yaw error near the attitude-hold deadband limit. The pilot sees only a composite of the translation and attitude errors from the reticle crosshairs, which indicate that the ADV docking port is to the right of the TDV docking port. This may prompt the pilot to apply a THC input to the left, which would further increase the translational error. If there was some indication that the attitude-hold system would soon yaw the vehicle to the left, the pilot may wait for the trajectory to evolve before making an erroneous THC input. Knowledge of the docking port position error decomposition into translation and attitude error components could help the pilot make appropriate decisions about THC inputs.

Figure 3 shows a square box around the reticle crosshairs displayed on the centerline camera view. This attitude deadband box indicates the ADV pitch and yaw attitude error magnitudes relative to the attitude-hold deadbands. The pitch and yaw attitude errors are referenced to the nominal attitude-hold values established by the attitude alignment maneuver before final approach for docking. If the center of the box coincides with the crosshair intersection, then the yaw and pitch errors are zero; if a border of the box lies along a crosshair, then the corresponding attitude error is at a deadband limit. The example in Fig. 3 indicates that the ADV is pitched down and yawed right and that these attitude errors are roughly half of the corresponding attitude deadband limits.

B. Flight-Path Marker

The aircraftlike symbol in Fig. 3 is a flight-path marker, which indicates that if the current ADV attitude and translational velocity were to persist, the ADV's docking port center would make contact below and to the right of the TDV's docking port center. First, the spatial orientation of the translational velocity vector of the ADV c.m. relative to the TDV c.m. is determined. Next, a straight line originating from the center of the ADV dock is drawn parallel to this relative velocity vector. Finally, the intersection of this line with the TDV dock plane is determined, and the flight-path marker is placed at that point.

C. Translational Flight Director

The number and directionality (right/left and up/down) of THC inputs required for a successful docking are indicated by a string of dots superimposed on the reticle crosshairs. The illustration in Fig. 4 indicates that the pilot should make three THC inputs upwards and two inputs to the left. The guidance algorithm is a state-feedback law that has two phases. The goal of the first phase is to eliminate any transverse offsets by nulling the radial position error and radial velocity before the axial distance between the two docking ports drops below 3 ft (0.9 m). The second phase provides fine tuning to compensate for drift, arising from deadband and orbital mechanics effects, by minimizing the projected radial position error at docking port contact.

D. Feedforward Control

The rotational motion induced by translational control inputs can adversely affect handling qualities for docking [29]. This happens because a conventional system for automatic attitude hold is reactive in nature, using a phase-plane controller that fires RCS jets to counteract the induced rotational motion after it exceeds a specified deadband. Feedforward control is proactive in nature and attempts to eliminate the induced rotational coupling by simultaneously firing RCS jets for translation and rotation. For example, a feedforward controller would estimate the undesired nose-right yawing moment that would arise from a left THC input, and it would fire RCS jets to simultaneously provide a left-pointing force as well as a nose-left yawing moment that cancels out the translation-into-rotation coupling effect. In practice, the coupling effect is not completely cancelled, but is greatly attenuated. The operation of the feedforward control system is transparent to the pilot; the vehicle responds as if it had very low translation-into-rotation dynamic coupling.

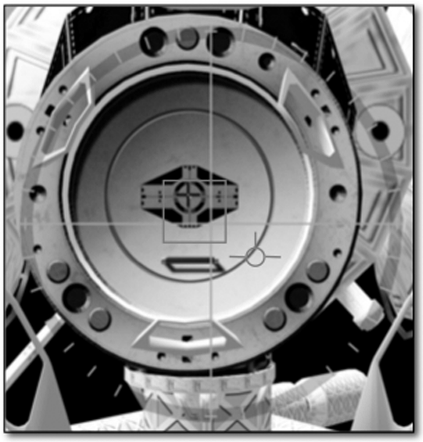

Fig. 3 Deadband indicator and flight-path marker.

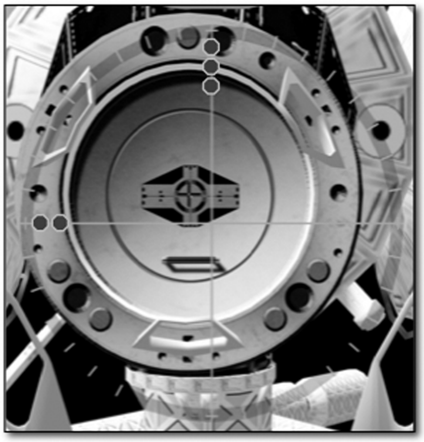

Fig. 4 Translational flight director.

A convex optimization software package in MATLAB® was employed to determine, subject to propellant considerations, optimum RCS jet firing times to cancel the angular rates arising from dynamic coupling effects in response to translation commands. The cost function J employed in calculating firing times for the feedforward controller is

$$J = \|\boldsymbol{A}\Delta t - \Delta \boldsymbol{v}\|_1 + \mu \sum_i [\Delta t_i] \tag{1}$$

In the equation above, $\boldsymbol{A}$ is the matrix of vehicle translational and rotational accelerations resulting from the firing of each RCS jet, $\Delta \boldsymbol{t}$ is the vector set of firing time durations for all RCS jets, and their product represents the resulting translational and rotational velocity components. $\Delta \boldsymbol{v}$ is the vector set of three translational velocity components (target values commanded by THC inputs) and three angular velocity components (target values of zero) that the RCS jet firing is trying to achieve. The resulting difference vector is reduced to a scalar using the 1-norm, which simply sums the absolute values of each of the vector components; this quantity is a measure of the precision with which the target velocity components are met. The parameter μ is a weighting factor that trades the relative importance of propellant usage (which is directly proportional to RCS jet firing time) against the precision with which the target velocity components are met, and i is an index representing each RCS jet.

The calculations also incorporated some operational constraints. In this work, the minimum on-time for RCS jets was modeled as 40 ms and the firing time durations were rounded to 10 ms. Because of these constraints the smallest rotational/translational impulse provided by RCS jets cannot be made arbitrarily small, which limits the fineness of control. Consequently, although the effects of dynamic coupling are greatly attenuated, they cannot be entirely eliminated. The process of attenuating dynamic coupling along one axis also introduces a small amount of coupling into the other two axes; this is due to the firing time constraints mentioned above and asymmetrical arrangement of RCS jets relative to the vehicle c.m. Errors in estimates of vehicle mass/inertia properties and RCS jet thrust vectors will also result in some residual coupling effects, although such errors were not modeled in this work. For this best-case scenario where actual vehicle properties match the vehicle model used by the control law, it was determined through analysis that the implementation of feedforward control employed in this work attenuates translation-into-rotation coupling by at least 98% relative to the baseline of no feedforward control.

The optimization program was run offline for a wide range of values of the weighting factor, μ, and the firing time constraints discussed above were subsequently applied to calculate the resulting velocity components. The set of firing time durations employed in the simulation corresponded to the value of μ that resulted in the lowest value of the maximum of the three angular velocity components. This process was done for each of the four pertinent THC inputs (left, right, up, down) by proper choice of the vector $\Delta \boldsymbol{v}$; the resulting jet firing times were stored and recalled for on-line use as necessary.

IV. Experiment Design

The principal objective of this experiment was to evaluate the effect of various piloting tools on spacecraft handling qualities for Earth orbit docking. This section describes various aspects of the experiment design.

A. Flying Task

The task selected was the final phase of docking operations during which the ADV was on final approach along the orbital velocity vector of the TDV (i.e., the V-bar approach). In this experiment, the TDV was in a circular orbit 217 miles (350 km) above the surface of the Earth, and it experienced no perturbations in position or attitude during the simulation run. At the start of the simulation run, the ADV was in essentially the same orbit as the TDV and was positioned slightly ahead of the TDV with the ADV's nose pointed opposite to the direction of its own orbital velocity vector. The axial distance between the ADV and TDV docking ports was 10 ft (3 m) and the relative axial closing speed was 0.1 ft/s (3 cm/s), resulting in a nominal run time of 100 s.

To provide sufficient piloting challenge and expose any handling qualities issues, a radial offset error was applied to the initial position of the ADV docking port relative to the TDV docking port. This resulted in two piloting subtasks:

1) Make coarse trajectory changes to align the centerline of the ADV docking port with the centerline of the TDV docking port.

2) Make fine trajectory changes as necessary to maintain this alignment.

To compare the levels of pilot compensation for these subtasks, two types of approaches were designed: offset and nominal. The offset approach began with a large (operationally unlikely) radial position error of about 4.25 ft (1.3 m), while the nominal approach began with a small (operationally likely) radial position error of about 6 in. (15 cm).

B. Experiment Matrix

The primary objective of this experiment was to evaluate the effect of various piloting tools, individually and in selected combinations, on spacecraft handling qualities for Earth orbit docking. Secondary objectives were to evaluate the effects of attitude-hold deadband size and the magnitude of initial position errors (nominal vs offset approach) on handling qualities for Earth orbit docking. The experiment matrix depicted in Fig. 5 shows the 24 test configurations for data collection.

C. Evaluation Pilots

Twelve experienced test pilots provided data for this experiment; they had an average of 6500 flight hours in a variety of

Piloting Tools* → **Run type** ↓	None	Dead-Band Indicator (DBI)	Flight-Path Marker (FPM)	Translational Flight Director (TFD)	DBI + FPM	TFD + DBI + FPM	Feed-Forward Control (FFC)	FFC + DBI + FPM
Offset approach 0.25 deg deadband								
Nominal approach 0.25 deg deadband								
Nominal approach 0.5 deg deadband								

* In addition to reticle, which was available for all piloting tool configurations

Fig. 5 Experiment matrix.

fixed/rotary-wing aircraft. Two were NASA pilots with decades of aircraft flight test/simulation experience. The other 10 were current/retired NASA pilot astronauts from the space shuttle program; they had flown a total of 11 missions as pilot and eight missions as commander. Many of the astronauts had performed actual spacecraft dockings, and most of them had received extensive simulator training on rendezvous/docking operations. Each pilot was available to the experimenters for about 8 h, and this time constraint was incorporated into the experiment design.

D. Training Procedures

Upon arrival, pilots received a detailed briefing on the experiment background and objectives, flying task, piloting tools, experiment matrix, and data collection procedures. Including discussion time with the experimenters, this session lasted approximately 1 h. This was followed by a training and familiarization session (about 1 h) in the simulator cockpit, where pilots practiced the flying task for various representative configurations drawn from the experiment matrix, until they felt comfortable that most of the learning curve was behind them.

E. Data Collection Procedures

Each pilot encountered the various experiment configurations in a different sequence. To avoid bias, the pilots were not told the value of the attitude-hold deadband and whether the feedforward control system was on. At the end of each simulation run, relevant docking contact performance parameters (see Table 1) were displayed to the pilot and experimenters. The values of adequate performance bounds for these parameters were derived from latching limits of the docking mechanism; desired performance limits included approximately half of the tolerances for adequate performance. The docking contact performance parameters were color-coded green for desired, yellow for adequate, and red for inadequate. For each test configuration, the pilot flew two formal evaluation runs with an option for a third run if necessary (e.g., significant difference in docking performance across the first two runs) and then provided experiment data for that test configuration as described below.

In handling qualities experiments, pilots are generally asked to make a composite assessment of the overall performance across all formal evaluation runs for a test configuration. This assessment takes into account not just the quantitative evaluation of the endpoint (e.g., docking contact) performance but also a qualitative evaluation of the manner in which the vehicle gets to the endpoint. This overall assessment of desired, adequate, or inadequate performance is used for traversing the decision tree in the Cooper–Harper chart [1]. Pilots use the Cooper–Harper scale to assign handling qualities ratings from 1 (best) to 10 (worst) based on their assessment of task performance and required compensation. It is an ordinal scale, which means, for example, that the difference between ratings of 1 and 2 is not the same as the difference between ratings of 3 and 4. Ratings of 1, 2, and 3 on the Cooper–Harper scale correspond to level 1 handling qualities, which are a general requirement for normal operations of flight vehicles. Desired performance is necessary, but not sufficient, for level 1 ratings. Ratings of 4, 5, and 6 correspond to level 2, which may be acceptable for some offnominal conditions, and ratings of 7, 8, and 9 correspond to level 3, which is acceptable only for transition to a safe mode after a major failure or disturbance.

After making a composite assessment of the overall performance across the formal evaluation runs for a test configuration, pilots assigned a handling qualities rating for that test configuration. The pilots also assigned ratings for each of the six components of the NASA task load index [30]. These six components were physical demand, mental demand, temporal demand, performance, effort, and frustration. The relative weighting of these six components for the docking task was determined by a pilot questionnaire at the end of the experiment. As appropriate, pilots provided qualitative comments about the test configuration they had just evaluated. All pilot commentary was recorded on electronic media while the experimenters separately noted key comments and observations.

After all test configurations had been evaluated, there was a debrief session. The pilots filled out a one-page questionnaire designed to elicit high-level comments on cockpit displays, out-the-window displays, piloting tools, motion cues, and experiment design. This was followed by a discussion with the experimenters on the pros and cons of the various test configurations.

V. Simulation Environment

The experiment was conducted on the vertical motion simulator (VMS) at the NASA Ames Research Center. The VMS is a large motion travel simulator [31] that has been used for numerous handling qualities evaluations [32]. Six-degree-of-freedom simulator motion was used for the experiment, although the motion cues for this task were very subtle. A single pilot seat was installed in the center of the simulator cab, with a researcher/observer seat immediately aft of the pilot seat. A three-axis THC was installed on the left side of the pilot seat. Although a three-axis rotational hand controller was installed on the right side of the pilot seat, it was not used in this experiment, consistent with current operating procedure in the final phase of docking. An illustration of the cockpit layout including the two hand controllers is shown in Fig. 6.

A. Displays

A simulated view of the TDV (represented by a model of the International Space Station) was projected on a set of three wide-angle collimated color displays with an image resolution of $1/2$ pixel per arcmin. The window display had a large field of view: 48 deg vertical and 120 deg horizontal. Window masking was not used in the simulator cockpit and therefore the entire field of view was available to the pilot. This is not representative of actual operations where the pilots have only a limited field of view through small windows. However, the docking task in this experiment was essentially a head-down task, and the pilot's attention was focused primarily on the cockpit instrumentation; the view outside the cockpit was used only for general situational awareness.

The cockpit console had three 6.5 in. (16.5 cm) color flat panel displays, the contents of which are shown in Fig. 7. The center panel displayed reticle crosshairs on a simulated view from a camera mounted on the centerline of the ADV dock; additional piloting tools were overlaid on this display as appropriate for the test configuration. The TDV docking port is the ring with numerous holes and three petal-like objects in the center of this display. The right panel displayed an attitude director indicator (ADI) and tapes showing range and range rate of the ADV's docking port relative to the TDV's docking port. The left panel displayed color-coded end-of-run data on several performance parameters at docking port contact, such as radial position error and relative angular rates; this panel was blank during the run. Pilots primarily used the center panel display to perform the assigned docking task.

Table 1 Desired and adequate docking performance bounds

Docking parameter	Desired	Adequate
Radial position error	1.5 in. (3.8 cm)	1.5 to 3.2 in. (3.8 to 8.1 cm)
Angular error magnitude	Roll: 1.5 deg. Pitch-yaw vector: 1.5 deg	Roll: 1.5 to 3 deg. Pitch-yaw vector: 1.5 to 3 deg
Axial closure rate	0.075 to 0.125 ft/s (2.3 to 3.8 cm/s)	0.05 to 0.075 or 0.125 to 0.15 ft/s (1.5 to 2.3 or 3.8 to 4.6 cm/s)
Radial velocity magnitude	0.075 ft/s (2.3 cm/s)	0.075 to 0.15 ft/s (2.3 to 4.6 cm/s)
Angular rate magnitude	0.075 deg/s (each axis)	0.075 to 0.15 deg/s (each axis)

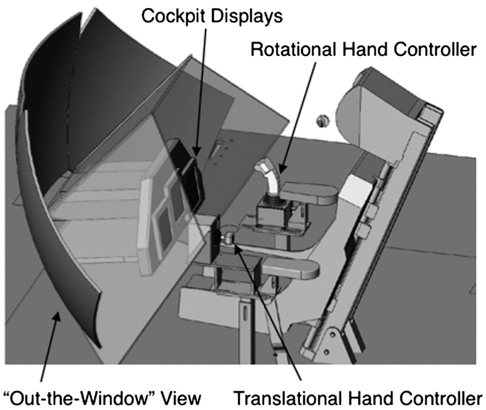

Fig. 6 Simulator cockpit layout.

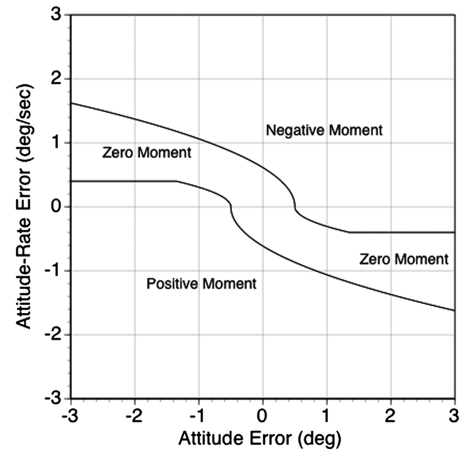

Fig. 8 Switching curves for pitch attitude hold with 0.5 deg deadband.

B. Dynamics and Control Model

A dynamics and control model was implemented in the VMS, as described below. The translational and rotational motion of the spacecraft, including primary orbital mechanics effects, was modeled using the flight dynamics model described in [29]. This model neglects third-body and Earth-oblateness gravitational effects because they do not significantly affect the dynamics of the docking task in this experiment. The six-degree-of-freedom Earth-relative motion of both the ADV and TDV were modeled separately, rather than using an approximate model for the dynamics of relative orbital motion between the ADV and TDV.

An ADV model was developed for this experiment using a preliminary version of Orion vehicle design data. That design information included the RCS jet locations and thrust forces, vehicle dimensions, mass properties, and some other pertinent details, but did not include control system or cockpit display designs. Research prototype control systems and cockpit displays were independently developed for this experiment. In the basic translational control system configuration (feedforward control off), the level of translation-into-rotation coupling was 5 deg/ft (16.4 deg/m) in the pitch and yaw axes.

The docking task in this experiment used only the attitude and translation RCS jets on the service module; hence, neither the auxiliary thrusters nor the additional RCS jets used for command module reentry were modeled. The jets of interest were located in four groupings, or quads, around the circumference of the service module, towards the aft end of the spacecraft. Each quad consisted of four jets, two angled forward and two angled aft, for a total of 16 RCS jets. The thrust dynamics model of each RCS jet included a time delay, a minimum firing duration, and a minimum time interval between sequential firings.

The control response type in the translational axes corresponded to a discrete velocity-increment mode. Displacement of the THC out of detent commanded the appropriate RCS jets to fire for a precalculated time interval, resulting in a fixed velocity increment of 0.01 ft/s (0.3 cm/s); the THC had to be returned to detent before another command could be issued. This response type is similar to that used by the space shuttle during docking operations. It was also the highest-rated translational control response type in the previous handling qualities study [29].

The control response type in the rotational axes was RCAH. The pilots were instructed not to make any rotational control inputs, and hence the rotational control system was always in attitude-hold mode. This attitude-hold function was implemented using phase-plane switching curves, which represent the edges of a deadband within which the RCS jets do not fire. As an example, the pitch-axis switching curves are shown in Fig. 8; the switching curves for the roll and yaw axes have similar shapes.

RCS jet firings generated by the attitude-hold logic were assigned higher priority, in order of pitch, then yaw, then roll; THC commands received lower priority. The 16 RCS jets were divided into two independent and fully redundant strings (A and B) consisting of eight jets each. In this simulation, the two strings could be used individually or together. Pulse-width modulated thrust profiles were not used. Instead, THC commands requiring RCS jets already in use were placed in a command queue, awaiting execution until a string became available and there were no higher-priority commands in the queue. When a string became available at the THC priority level, the first THC command in the queue was converted into RCS jet firing times and assigned to that string for execution. The lookup table used for conversion of THC commands into RCS jet firing times was determined by the THC mode selected: either basic or feedforward control. In theory, the two RCS jet strings could become saturated with commands. In practice, for the runs during this experiment, there were almost no instances where a pilot's THC command was noticeably "queued" (and therefore delayed).

VI. Results

The formal evaluation period in the VMS was 27 May through 13 June 2008. A total of 617 formal evaluation runs were made during this experiment. The 12 evaluation pilots provided

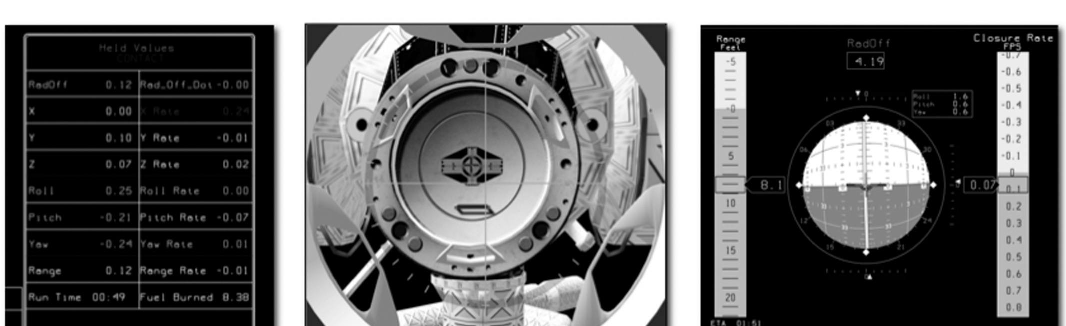

Fig. 7 Cockpit displays.

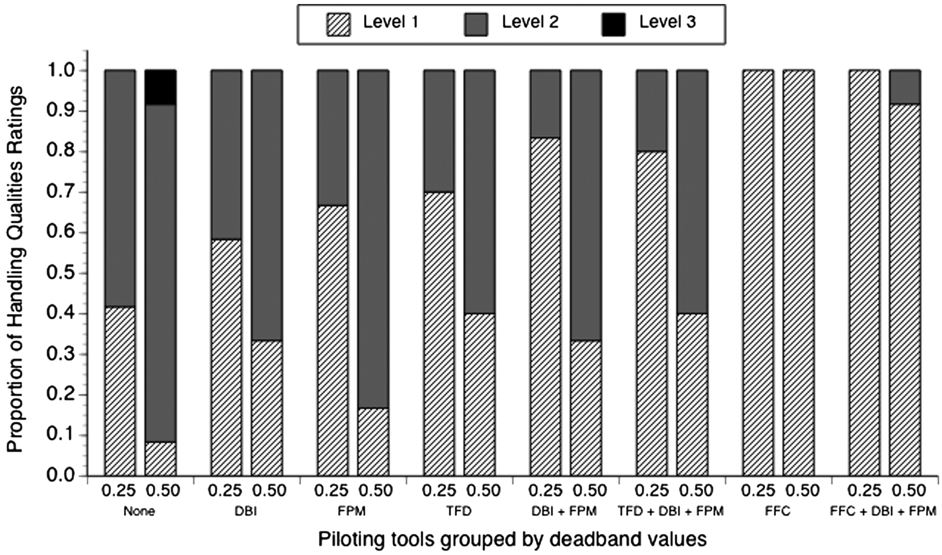

Fig. 9 Handling qualities ratings for nominal approach with 0.25 and 0.5 deg deadbands.

Cooper–Harper ratings, NASA task load index (TLX) component ratings, and specific comments for each of the test configurations; these results are presented below.

A. Handling Qualities Ratings

Cooper–Harper rating data are shown in Figs. 9 and 10 for various piloting tools, individually and for the combinations evaluated in this experiment. In Fig. 9 the paired bars enable a comparison across 0.25 and 0.5 deg deadbands for the nominal approach, while in Fig. 10 the paired bars enable a comparison across nominal and offset approaches for the 0.25 deg deadband. The crosshair reticle on the camera view was present for all piloting tool configurations. As an example, the leftmost bar in Fig. 9 indicates that for the test configuration of no tools and offset approach, about 40% of the pilots gave a level 1 rating, about 60% gave a level 2 rating, and there were no level 3 ratings.

The data in Fig. 9 show that the 0.25 deg deadband substantially improves handling qualities relative to the 0.5 deg deadband, for all piloting tool configurations without feedforward control. For a fixed value of deadband, the use of piloting tools improves handling qualities relative to the corresponding baseline of no tools (i.e., reticle only). The extent of improvement depends on the tool(s). The two configurations with feedforward control are the only ones that received a level 1 rating from virtually all pilots, and they correspond to the piloting tool configurations with the best handling qualities. The deadband indicator, flight-path marker, and translational flight director each provide a modest improvement in handling qualities. The combination of deadband indicator and flight-path marker received good ratings as well as favorable pilot comments. Providing deadband indicator and flight-path marker in addition to feedforward control did not make a significant difference.

Pilot comments showed a strong preference for feedforward control because it greatly attenuated the effects of translation-into-rotation coupling. Comments about the deadband indicator and flight-path marker were quite positive because these tools helped the pilots compensate for dynamic coupling effects in test configurations with feedforward control off. Some pilots suggested that the deadband box and flight-path marker would be useful in a backup mode if the feedforward controller failed. In an actual implementation, an on/off (declutter) function would be desirable. Comments about the translational flight director were generally neutral or mildly negative, although the rating data indicated some improvement in handling qualities relative to the baseline (no-tools) configuration.

The docking task in this experiment had two piloting subtasks:

1) Make coarse trajectory changes to align the centerline of the ADV's docking port with the centerline of the TDV's docking port.

2) Make fine trajectory changes as necessary to maintain this alignment.

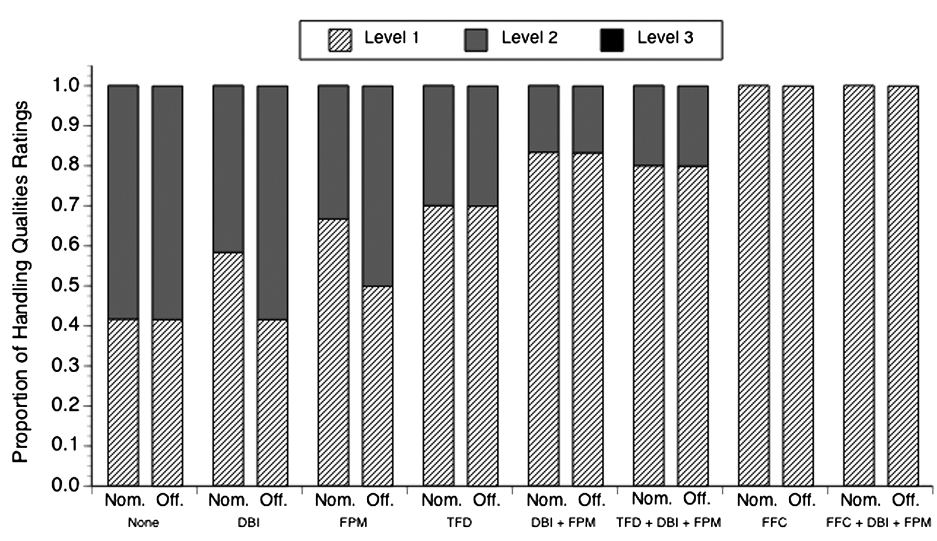

Fig. 10 Handling qualities ratings for 0.25 deg deadband with nominal and offset approaches.

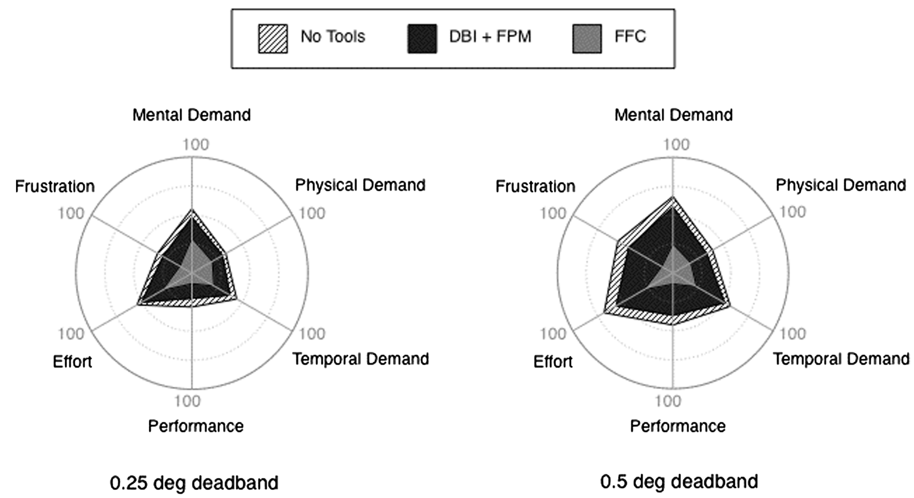

Fig. 11 Task load index component ratings for selected piloting tools with nominal approach.

The first subtask was significant for the offset approach and negligible for the nominal approach, while the second subtask was essentially the same for both the offset and nominal approaches. The data in Fig. 10 show similar handling qualities ratings for nominal and offset approaches, regardless of piloting tool configuration. Pilot comments were consistent with the rating data. This indicates that the second subtask, making fine trajectory changes to maintain alignment between the two docking ports, is the dominant one for the overall docking task.

B. Task Load Index Component Ratings

NASA task load index component ratings (averaged across all pilots) are shown in Fig. 11 for selected piloting tools: deadband indicator, deadband indicator plus flight-path marker, and feedforward control. The crosshair reticle on the camera view was present for all piloting tool configurations. There are two sets of data shown in Fig. 11, corresponding to 0.25 and 0.5 deg attitude-hold deadbands. Although TLX component ratings are typically combined into a single workload score, this analysis highlights the component ratings to provide some insight about the various aspects of pilot workload for the docking task.

It is evident that the smaller (0.25 deg) deadband substantially decreases all task load components for tool configurations without feedforward control. Relative to the baseline of no tools (i.e., reticle only), the combination of deadband indicator and flight-path marker provides a modest reduction in pilot task load while feedforward control provides a significant reduction in pilot task load. It can be seen that the primary task load components for this flying task are mental demand, temporal demand, and effort, while the secondary components are physical demand, performance and frustration.

C. Propellant Usage

The average propellant consumed per docking for nominal approach is shown in Fig. 12 for various piloting tools, individually and for the combinations evaluated in this experiment. The propellant usage with feedforward control was lower than that of piloting tool configurations without feedforward control, indicating that feedforward control improved handling qualities while decreasing propellant usage. Relative to the baseline (no-tools) configuration, feedforward control reduced propellant usage by 25% for the 0.25 deg deadband case and 43% for the 0.5 deg deadband case. For the baseline (no-tools) configuration, the propellant usage for the 0.25 deg deadband case was 24% less than that for the 0.5 deg deadband case.

With feedforward control off, translational control requires approximately 0.09 lbm (0.04 kg) of propellant to provide the desired

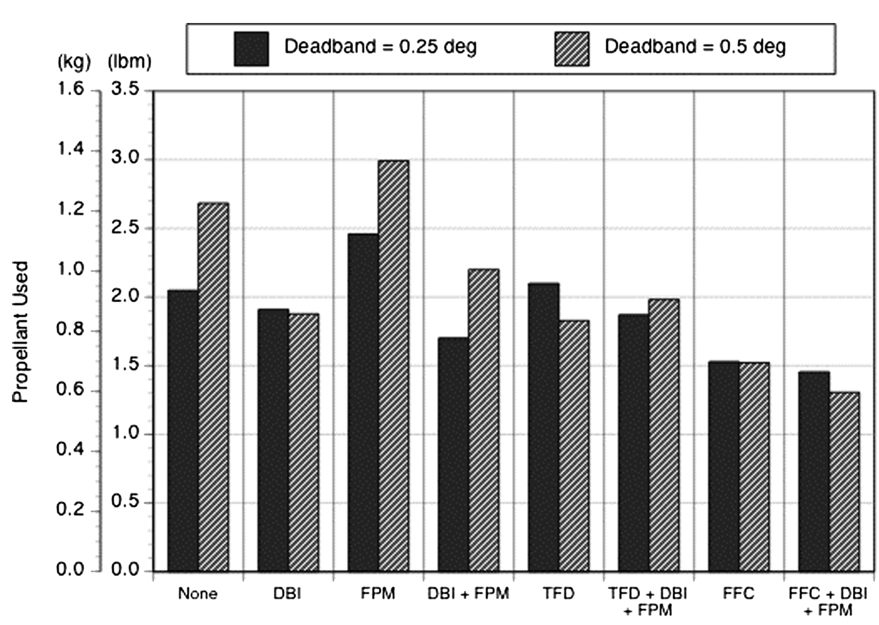

Fig. 12 Propellant usage for various piloting tools with nominal approach.

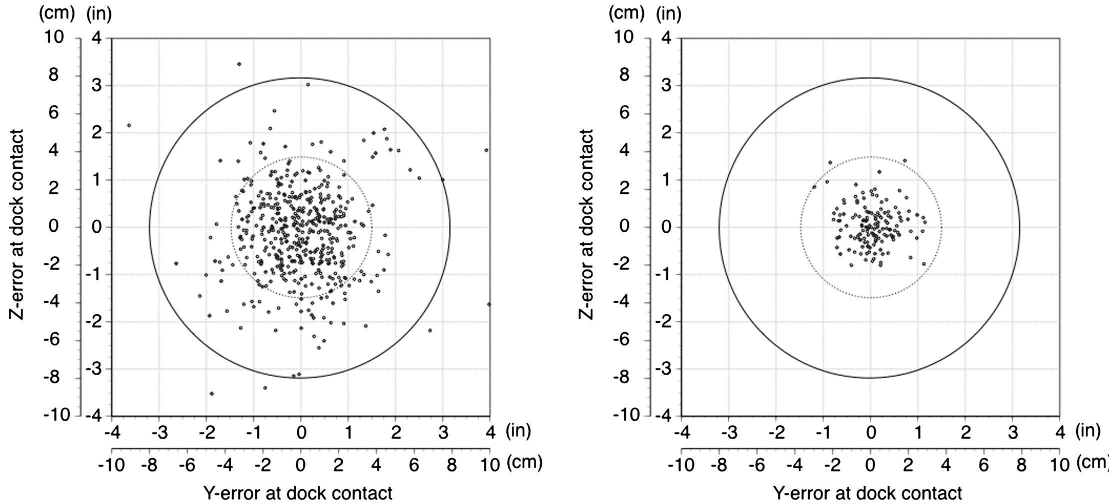

Fig. 13 Docking position errors for feedforward control off (left) and feedforward control on (right).

speed change of 0.01 ft/s (0.3 cm/s) for each THC input. Because of inertial coupling effects, the RCS jet firings for translational control also induce pitch/yaw motion. This activates the attitude control system that commands RCS jet firings to hold attitude within the specified deadband (0.25 deg or 0.5 deg in this experiment); hence, additional propellant is consumed. Including propellant consumed by the attitude-hold function, the total propellant usage per THC input for the baseline (no-tools) configuration averaged 0.18 lbm (0.082 kg) for the 0.25 deg deadband and 0.15 lbm (0.068 kg) for the 0.5 deg deadband. Hence, with the tighter (0.25 deg) deadband, the propellant consumption per THC input was 20% more than that with the looser (0.5 deg) deadband; this result is consistent with intuition because the attitude controller has to work harder to enforce a tighter deadband. However, the more predictable trajectory for the 0.25 deg deadband case generally required fewer adjustments by the pilot. For the baseline (no-tools) configuration, the experiment data showed 34% fewer THC inputs for the 0.25 deg deadband case relative to the 0.5 deg deadband case. As a result, the total fuel usage for the tighter (0.25 deg) deadband case was 24% lower than that for the looser (0.5 deg) deadband case.

With feedforward control on, THC inputs command RCS jets firings to provide simultaneously a translational force as well as a rotational moment, which practically eliminates translation-into-rotation coupling effects. Hence, there is practically no demand on the attitude-hold function between THC inputs. This is confirmed by the experiment data in Fig. 12, which show practically no difference in propellant usage between the 0.25 and 0.5 deg deadband cases with feedforward control on. For the 0.25 deg deadband case, experiment data showed that the number of THC inputs with feedforward control on was 8% less than that for feedforward control off. Also, the average propellant usage per THC input was 0.14 lbm (0.064 kg) with feedforward control on versus 0.18 lbm (0.082 kg) with feedforward control off. Because of the combined effects of these advantages, for the 0.25 deg deadband case, the total propellant usage with feedforward control on was 25% less than that with feedforward control off.

The above results for propellant usage can be summarized as follows. In the no-tools configuration, using a 0.25 deg deadband reduces propellant usage by 24% compared with using a 0.5 deg deadband. Using feedforward control further reduces propellant usage by 25% relative to the 0.25 deg deadband case with no tools.

D. Docking Performance

The relevant parameters for docking performance are given in Table 1; position error is a key parameter. Position errors at docking port contact (soft dock) are shown in Fig. 13. The smaller circle represents the error bound of 1.5 in. (3.8 cm) for desired performance and the larger circle represents the error bound of 3.2 in. (8.1 cm) for adequate performance. An outlier data point with a radial position error of 6.3 in. (16 cm) was cropped from the left plot to provide a better visual scale in Fig. 13.

Data analysis showed that 99% of all formal evaluation dockings were within the bound of adequate performance for position error. For configurations without feedforward control (left plot), 80% were within the desired performance bound for position error. This indicates that even for configurations without feedforward control, pilots were generally able to achieve the desired level of performance and the level 2 handling qualities ratings can be attributed primarily to the substantial level of pilot compensation necessary to achieve that performance. Feedforward control improved docking performance: it was found that 99% of such dockings (right plot) were within the desired performance bound for position error. It is evident from the data shown in Fig. 13 that the mean position error with feedforward control on is significantly less than that with feedforward control off.

VII. Conclusions

An evaluation of handling qualities for spacecraft docking in Earth orbit was conducted by 12 pilots, including 10 astronauts, flying the NASA Ames Vertical Motion Simulator. The objective was to study the effects of various piloting tools on handling qualities of a spacecraft with significant translation-into-rotation coupling, for the task of translational control during the final phase of docking. Four piloting tools were designed with the goal of enhancing handling qualities: deadband indicator, flight-path marker, translational flight director, and feedforward control. Handling qualities with these tools, individually and in selected combinations, were compared with a baseline no-tools configuration.

The baseline no-tools configuration had unsatisfactory handling qualities due to the effects of translation-into-rotation coupling: almost 60% of the pilots gave it a level 2 rating while the remainder gave it a level 1 rating. Use of deadband indicator, flight-path marker, and translational flight director, individually and in selected combinations, improved handling qualities but did not make them solidly level 1. Using feedforward control yielded a substantial improvement in handling qualities (virtually all ratings were level 1) while reducing propellant usage relative to the no-tools configuration by 25% for a 0.25 deg deadband and 43% for a 0.5 deg deadband.

For piloting tool configurations that did not use feedforward control, it was found that a lower deadband for attitude hold (0.25 deg vs 0.5 deg) substantially improved handling qualities while generally reducing propellant usage. It was also found that the subtask of making fine trajectory changes to maintain alignment between the two docking ports dominates the overall docking task during final approach.

Acknowledgments

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